REDUNDANCY GAIN: CORRELATIONS ACROSS S SENSORY MODALITIES FRAOM A NEUROLOGICALLY NORMAL POPULATION

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REDUNDANCY GAIN: CORRELATIONS ACROSS S SENSORY MODALITIES FROM A NEUROLOGICALLY NORMAL POPULATION

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I dedicate this work to Jesus and Darwin, who will fight an epic battle on the day of the apocalypse.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Visual Working Memory Task Accuracy (%)
CUD	Crossed-Uncrossed Difference
CDF	Cumulative Distribution Function
CRT	Cathode Ray Tube
EEG	Electroencephalogram
Hz	Hertz
Min	Minimum
ms	Milliseconds
PC	Personal Computer
RMVI	Race Model Violation Index
RT	Reaction Time
SOA	Stimulus Onset Asynchrony
t	Time

SUMMARY

One of the most basic reaction time experiments employed by psychologists is the comparison of latencies to responses for single and redundant targets. The general effect is that participants are capable of responding faster, that is having shorter response latencies when redundant stimuli, as opposed to an individual stimulus, are presented. Interestingly, several models attempting to predict this effect, including the well known race model, have not been entirely successful. The following study evaluated redundancy gain and violations of the race model, in three experimental models: visual only, auditory only, and a visual-auditory bimodal paradigm. The results showed redundancy gain in all three paradigms, but they were only significant violations of the race model for the visual-auditory condition. Additionally, correlations between the different paradigms were explored with respect to redundancy gain and violations of the race model on an individual participant basis.

CHAPTER 1

INTRODUCTION

One of the most basic reaction time experiments employed by psychologists is the comparison of latencies to responses for single and redundant targets. A redundant target is prototypically defined as a second target stimulus that coincides with the first (e.g. presenting a white flash to both the left and right visual field simultaneously). The general effect is that participants are capable of responding faster (having shorter responses latencies) when redundant, as opposed to when single, target stimuli are presented. This gain in speed with redundant targets has various names but is most commonly referred to as the redundancy gain or redundant target/signal effect. The discovery of this phenomenon has lead to the development and necessary refinement of predictive models. The first model, based on the work of Raab (1962) suggested that simple statistical facilitation could account for the enhancement, that is the processing of each stimuli is independent and stochastic, and the first to be processed will drive a motor response (i.e. the so called race model). In general, these models have progressed from independent to integrative or coactivation processing models (Mulligan & Shaw, 1980, Miller, 1982). Interestingly, the fundamental assumptions of these models were challenged by the result of one study evaluating redundancy gain in patients who have undergone surgical sectioning of the corpus callosum, so called split brain patients (Reuter-Lorenz, Nozawa, Gazzaniga, & Hughes, 1995). While this paradoxical result has captured the attention of scientists and research with redundancy gain in split brain patients has advanced, work with a neurologically normal population has stagnated, which has left unresolved questions.

Independent Processing Model

The earliest and simplest independent processing model of redundancy gain effects was proffered by Raab (1962). This work suggested that each stimulus was received and processed by separate channels. These channels could then independently generate a response once the activation from the stimulus reached a particular threshold. Within this model, it assumed that the processing times associated with each channel are stochastic and a cumulative distribution function of total reactions times for each channel can be generated. If the two distributions overlap and the two channels “race” with each other, redundant targets should statistically have faster response times, on average, when compared to single channels. Stated another way, each channel has a certain proportion of their distributions falling below a particular reaction time. If the race model is accurate, then the cumulative distribution function for the redundant condition should be bound by the sum of those proportions at the given reaction time (for the single stimuli conditions) minus the joint probability of both conditions . For example, if, in the auditory condition, the reaction time 175 ms may mark the 0.35 proportion, whereas in the visual condition it marks the 0.05 proportion, in the redundant condition 0.3825 (0.35 + 0.05 - 0.35 * 0.05) of the reaction times should fall below the 175 ms mark, but certainly no more than 0.3825. Notice, that also means there should be more reactions times below the 175 mark for the redundancy conditions, which in turn means the average reaction time for the redundant conditions should be shorter.

Coactivation Models

While the conceptualization of racing channels seemed parsimonious and had experimental evidence to substantiate the theory (Corcoran & Weening, 1969; Mulligan & Shaw, 1980), there were subsequent results presented that contradicted the predictions of the simple race model. Miller (1982) asserted that all race models must make very specific predictions concerning the reaction time distribution observed across both modalities and participants. These predictions must not be violated if the race model is to fully explain redundancy gain. Testing this assertion, Miller performed a bimodal experiment where the participants were presented with an auditory tone, visual stimulus and then both simultaneously (redundant condition).

Within this bimodal (i.e. two sensory modalities) framework, if one labels the reaction time for presentation of the visual stimulus as RT_V, the reaction time for auditory stimulus as RT_A, and the reaction time for the redundant presentation of both the auditory and visual stimuli as RT_R, then according to the race model the reaction time for the redundant condition is the minimum of the reaction time of the auditory stimulus or the visual stimulus. This is stated in the following equation:

$$RT_R = \text{Min}\,(RT_A, RT_v)$$

Following from this basic assertion, Miller (1982) derived an inequality with respect to the cumulative distribution functions of the reaction times for the single and redundant modalities. In his paper, Miller stated the following probability (S1 and S2 corresponding to the signal channels 1 and 2, or visual and auditory channels for the example presented above):

$$P(RT<t|S_1 \text{ and } S_2) = P(RT<t|S_1) + P(RT<t|S_2) – P[(RT<t|S_1) \text{ and } (RT<t|S_2)]$$

Where the left hand side of the equation corresponds to the CDF of the redundant signals condition, the initial two terms on the right side of the equation are the sum of the CDFs from each of the single stimulus conditions, which are generated with experimentation. The farthest term on the right hand side the probability that both S_1 and S_2 will result in reaction time t, which is not directly measurable. However, according to the race model, the two stimulus channels are independent (Raab 1962). Stated mathematically:

$$P[(RT<t|S_1) \text{ and } (RT<t|S_2)] = (P(RT<t|S_1) * P(RT<t|S_2)$$

Therefore:

$$P(RT<t|S_1 \text{ and } S_2) = P(RT<t|S_1) + P(RT<t|S_2) – (P(RT<t|S_1) * P(RT<t|S_1)$$

However, it should be noted that a more general statement can be made without making the assertion that the two stimuli channels are completely independent. By definition, a probability cannot be negative, therefore the joint probability, $P[(RT<t|S_1)$ and $(RT<t|S_2)]$ must be greater than zero. Miller (1982) taking that assertion into account, noted that the inequality below sets a boundary condition for nearly all race models where complete independence may not be asserted. Therefore, if the following inequalities is violated, it provides evidence the race model cannot account for the redundancy gain effects.

$$P(RT<t|S_1 \text{ and } S_2) \leq P(RT<t|S_1) + P(RT<t|S_1)$$

In terms of actual data analysis, the CDF provides a mechanism for summation of proportions for a given reaction time, thus making it possible to make boundary predications about redundant conditions, which provide a test boundary for race model testing. The CDF can be expressed in terms of function notion as:

$$F_r(t) \leq F_{S1}(t) + F_{S2}(t) \text{ for all } t$$

In the context of the visual-auditory paradigm, the end result suggests that the fraction of redundant signal responses (both visual and auditory) faster than time, *t*, should be less than or equal to the sum of the fraction of visual-signal responses faster than time, *t,* and the fraction of auditory-signal responses faster than time, *t*. Within the context of his bimodal redundancy experiment, Miller (1982) found that there were indeed violations to the inequality predicted by the race model. In particular, the violations tended to occur at the lower values of *t*. In other words, for the fastest reaction times within the CDF, there were faster responses to the redundant stimuli than the race model would predict from the distribution of single stimulus reaction times. These results suggested that there are at least some circumstances where the race model was an inadequate explanation of the redundancy gain. In effect, the violations of the race model suggest that the channels are not entirely processed independently.

In a redress to violation of the race model, Miller (1982) proposed that instead of the channels acting independently, the channels may have a common interaction point. Once reaching the interaction point, the signals sum to a common coactivation, which then may reach a response threshold at a decision point triggering a motor response (i.e. neural summation or coactivation). It should be noted that another possible approach is to look for models that are in the intermediaries between the race model and coactivation model. For example, the interactive race model proposed by Mordkoff & Yantis (1991) suggests there are two channels that are separable but are able to share specific types of information, though each channels makes a decision. They postulated two mechanisms for the information to cross between the channels, inter-channel cross talk and non-target driven decision bias. Inter-channel cross talk is the effect that one stimulus has on the processing of the other, that is information about the contingencies between two stimuli (if such a contingency exists). The idea being, the identity of one of the perceptual channels can have an effect on establishing the identity of information in the other perceptual channel. Importantly, this can have an enhancement effect only if the contingency establishes a redundant condition. Furthermore, as a subcomponent of the interactive race model, there is a potential for non-target driven response bias (again a contingency argument) that suggest non-targets can bias the response times. However, almost immediately the interactive race model was challenged and follow up work showed that the interactive race model could not account for all redundancy gain results (Morkdoff & Yantis, 1993, Mordkoff & Miller, 1993).

As the state of the redundancy gain literature stands, the coactivation model, at least at this juncture, is the most tenable explanation of the redundancy gain effects that show violations of the race model (e.g. Miller, 1982, 1986, 1991, 2004, 2007a, 2007b; Miller & Adams, 2006, Miller & Van Nes, 2007).

The following will provide a brief review on the testing and enhancement of the coactivation literature. As discussed briefly above, the initial impetus for pursuit of the coactivation model was the work of Miller (1982). In showing violations of the race model, he was able to propose and provide support for the coactivation model. The coactivation model held that instead of the channels working completely independently, it was more likely that the channels actually culminate at a common activation point. From the common activation point the processing leads to decision point and then a motor response generation. In follow-up work, Miller (1986), contrasted between the exponential and accumulation models. These models make specific predictions about the influence of "history" on activating a response that is in the accumulation model. For the case of the accumulation model, history contributes to the activity need to generate a response, whereas in the exponential model that is not the case. The methods for evaluating which of the two models is the most provides and insightful understanding of the models themselves. Miller's (1986) study proposed offsetting the synchronization of the visual stimulus from the auditory stimulus in a visual-auditory redundancy gain task. If the accumulation model is correct then presenting redundant targets with an asynchrony should show if there is a history of "activity" generated by the first single stimulus. The activity of the first stimulus could then be augmented by the occurrence of the second redundant stimulus. If there is not a history of activity, but rather the presence or absence of the effect for the single or redundant condition, then the most likely explanation is an exponential model. Miller (1986) derived the following inequality to test whether the exponential model is a valid model or not, below is the inequality:

$$\mathrm{F}_{\mathrm{r,SOA}}(t) < F_v(t) + \mathrm{F}_{\mathrm{a,0}}(t\text{-}\mathrm{SOA}_{\mathrm{A}}) \text{ for all } t.$$

Miller (1986) manipulated the SOAs at increments of 33 ms (33, 67, 100, 133 or 167 ms) between the visual and auditory stimuli. The results, of 2 participants, violated both the race model inequality and the exponential model inequality. Overall, this provided further evidence against the race model and for the coactivation model, in particular, one where activity accumulates and leads to a response, as opposed to a response being generated by an exponential process. The evidence suggests that the exponential model cannot explain the redundancy gain results.

Miller (1991) further explored the notion of a coactivation model, actually noting that up to that point it was defined as a model that "produces faster detection of redundant targets than the race model" (Miller 1991, Page 16). Basically, the coactivation model is defined as not being a race model. Therefore, Miller (1982), in an attempt to define the model more specifically, divided the idea of the coactivation model into two classes, the independent model and the interactive model. The independent model is defined as one where each channel in the model is able to generate its own activity with both combining at a common summation point before generating a response. The independent coactivation model can also have differential weighting of the channels, or the activity generated by the channels for a given stimuli. The interactive model of coactivation suggests that the interaction occurs when the two channels are processing the stimuli. In other words, the response activation in this model can depend on the information from both channels simultaneously, including when one stimulus affects the activation generated by the other stimulus on a second channel. Within the context of these two models, Miller (1991) postulated that if the independent activation model accounted for the redundancy gain, then there should only exist "main effects" in an analysis of variance for response activation. However, an interaction should exist in the response activation for the interactive model. In order to understand the theory, the first of two experiments is detailed here. The first experimental design varied the relationship between the redundancy gain pairs in a "pseudospatial" manner with high, medium or low spatial positions of the visual stimulus and high, medium, and low frequency tones. The targets can be congruent (e.g. high spatial position, high frequency) or incongruent (e.g. high spatial position, low frequency). The participants were tasked with responding when the auditory or visual stimuli were in the high and low conditions, but withholding their response when either both or one of the stimuli were presented in the middle condition (respective to high and low position and frequency). The results showed that the responses to incongruent trials were significantly slower than response to congruent trials. In effect, some characteristic of one stimulus affected the processing of the other in a significant way, leading to an interaction (i.e. support for the interactive model) and further evidence away from the race model or the independent coactivation model. Miller (1991) went on to perform a more stringent conditional redundant target presentation, also showing an interaction effect, which does not suffer from a high level or abstract relationship. Overall, the results point more towards an interaction coactivation model.

At this juncture, the redundancy gain literature shifted abruptly to work with split brain patients. Reuter-Lorenz, Nozawa, Gazzaniga, and Hughes (1995) conducted psychophysical work with patients who had their corpus callosum surgically sectioned as a treatment for intractable epilepsy. Interestingly, while these patients showed overall slower reaction times to stimuli when compared to controls (means around 400-500 ms for the split brain patient and 200-240 ms for controls), the difference in reaction time between the redundant and single stimulus condition was significantly larger than expected and was in clear violation of the race model inequality (~40 ms from the fastest single presentation for the split brain patient versus ~10ms for the controls). Importantly, conducting this work with split-brain patients introduced an anatomical foundation to the model testing of redundancy gain. In particular, the authors connected the race or coactivation model "channels" with the anatomy of the brain, where each hemisphere was suggested to be the corporeal version of the processing channel (e.g. visual information from left hemisphere is processed by the right side of the brain and vice versa), and that coactivation would occur via the corpus callosum. However, considering the results, if each hemisphere was a channel and the corpus callosum mediated the coactivation, by sectioning the hemisphere, it should provide the independent, competing channels proposed by the race model. Instead, the violation of the race model for a split brain patient then provides a paradox, since it suggests that neural summation is still occurring despite the loss of the most robust connection between the hemispheres. Reuter-Lorenz, Nozawa, Gazzaniga, and Hughes (1995), accounted for the results in part by suggesting a AND-OR model, which suggested that responses to the single stimuli were much slower, while responses to the redundant stimuli were closer to what is normally expected. However, that notion has been highlighted as having several points of contention (as detailed in Miller, 2004). While it is easy to become engrossed into these results and the follow-up studies, as many other scientists have done, the main focus of the work presented here is with neurologically normal patients. Just briefly, the current postulations hold that subthalamic routes may provide a source of interhemispeheric communication that can facilitate coactivation, suggesting perhaps that there are two potential venues for the redundancy gain coactivation to occur between hemispheres (Corballis, 1998; Roser and Corballis, 2002; Iacoboni, Ptito, Weeks, and Zaidel, 2000; Corballis, Corballis, and Fabri, 2004; Miller, 2004).

Miller (2004) incorporated the results from split brain patient work. In particular, Miller challenged the explanation proposed by Reuter-Lorenz , Nozawa, Gazzaniga, and Hughes (1995) by first suggesting that their AND-OR model is not testable in a quantitative fashion, given the level of detail provided about the model. Second, within the model, there is a suggestion that both inhibition and activation are occurring, which is inherently not parsimonious. Especially considering that RTs are typically thought to be generated by reaching enough activation or are generated with a loss of inhibition. Third, the model does not address the phenomena that co-occur in the individuals during the redundancy gain paradigm, such as the crossed-uncrossed difference (CUD). In response to these criticisms, Miller (2004) has put forth the hemispheric coactivation model, which generally holds that both hemispheres need to be activated (whether in the sensory areas, motor areas, or elsewhere) when responding to either a single or redundant stimuli to generate a response. Therefore, for split brain patients, the lack of communication between hemispheres is the cause of specifically enhanced redundancy gain for redundant conditions. The causality is a product of the contralateral organization of the brain. In particular information presented to one visual hemifield should be detected most quickly by the contralateral hemisphere. To generate activation in the ipsilateral hemisphere, the information passes through the corpus callosum; however, if that connection is severed, then it would have to be processed by the ipsilateral hemisphere via slower subcortical pathways. Hence, for unilateral stimuli, the response times should be slowed in the split brain patients since there is a delay for the two hemispheres to be active to generate a response. For redundant conditions, both hemispheres could receive information about the stimulus with within hemisphere pathways, thus leading to a faster response since both hemispheres could be active without relying on the slower subcortical pathways. With neurologically normal participants, the intact corpus callosum allows for fast interaction between the hemispheres for the unilateral stimuli condition, leading to faster response times for those conditions and a much smaller redundancy gain. Miller (2004) provides some simulations where there are systematic manipulations of the delays caused by the hypothetical "slower" pathway, which appear to conform to the results found in previous work (e.g. Reuter-Lorenz , Nozawa, Gazzaniga, and Hughes, 1995; Corballis (2002).

Since the inception of the hemispheric coactivation model, there have been several instances of follow-up research focusing on testing the model (Miller and Adams, 2006, Miller, 2007a, 2007b, Miller and van Nes 2007). Miller and Adams (2006) tested the notion of hemispheric coactivation by asserting that if both hemispheres are already active with another task, then the redundancy gain should be reduced in comparison to when both hemispheres are not already activated. Miller and Adams (2006) had their participants either respond in a “static condition” where they did not move their hands laterally and a “dynamic condition” where the patient’s hands and response platforms move laterally back and forth. The participants responded only to visual stimuli presented at eccentricity from the central fixation point, either unilaterally, bilaterally, or neither. The participants were required to respond to these stimuli with both index fingers at the presentation of either the unilateral or bilateral condition. The results indicate that the dynamic condition does indeed have a smaller redundancy gain when compared to the static condition, which according to Miller and Adams (2006) interpretation provides evidence for the hemispheric coactivation model. Furthermore, Miller (2007a) used a similar visual redundancy gain paradigm while taking electroencephalography measures (EEG), particularly looking at changes in potential around the motor sites of the brain. The results showed race model violations only at the two fastest percentiles of the distribution. Additionally, the EEG results suggest there is a potential response pattern that closely corroborates the coactivation model. Specifically, There are changes in the ipsilateral and contralateral hemisphere when generating a response to either unilateral or bilateral visual stimuli, which have a temporal course similar to that predicted by model as well. It is particularly worth detailing that while activity was expected to be robust in the contralateral hemisphere over the motor areas, when responding to the visual task, the main focus was the ipsilateral hemisphere, which also showed activity delayed from the contralateral hemisphere. The results were in line with the notion that both hemispheres are involved in generating a response to either unilateral or bilateral stimuli. Miller (2007b) focused on evaluating the notion that split brain patients enhancement of redundancy gain was the result of interhemispheric inhibition being eliminated with severing of the corpus callosum (Corballis, Hamm, Barnett, Corballis, 2002). Using several behavioral and EEG experiments, Miller and Adams (2006) were able to provide an extensive amount of evidence against the interhemispheric hemisphere explanation of enhanced redundancy gain. Finally, Miller and van Nes (2007) tested responses to visual stimuli with the left, right, and both hands. According to the hemispheric coactivation model, motor activation may involve the two hemispheres working together to generate a response. So therefore, a response generated from activity of both hemispheres reached more quickly leading to the observed enhancement of redundancy gain. In accordance with the prediction, when responding with either the left or the right hand, participants, showed no significant violations of the race model, however when responding with both hands the participants showed violations of the race model. The results corroborate the hemispheric coactivation model, in that when responding with both hands, the participants showed greater redundancy gain. Additionally, Miller and van Nes (2007) tested the idea that having the hemispheres already active may mitigate the redundancy gain, as in the case of Miller and Adams (2006); however, this was evaluated with the presentation of an auditory accessory stimulus. The redundancy gain results show that the addition of an auditory accessory stimulus (that was to be ignored) resulted in less redundancy gain when compared to the redundancy gain trials without the auditory stimulus, providing further evidence that corroborates with the hemisphere coactivation model.

Recent Neurologically Normal Redundancy Gain Studies

Past the work with the coactivation model, little work has been conducted on just understanding some of the basic psychophysics of the redundancy gain phenomenon. Additionally, little work is currently focused on understanding neurologically normal participants. Listed below are some of the exceptions to that assertion. Corballis (2002) conducted a redundancy gain study with normal participants. He used a visual redundant paradigm, where a white flash appeared either to the left, right or bilaterally on a black background. Additionally, he conducted the same test with the flashes being equiluminent to the background. The results from the participants did not violate the race model for visual only paradigm. These redundancy gain results corroborates with his previous control group for the split brain study (Corballis, 1998). It also corroborates the original split brain work conducted by Reuter Lorenz et al (1995) and some of the work of Miller and Nes (2007). While Corballis (2002) mentioned that in visual work nearly half of the individuals violated the race model (on the whole there was no violations), the actual breakdown of participants violating or not violating the model is completely unavailable in most studies.

Additionally, Schroter, Ulrich, and Miller (2007) have shown that pairing an auditory tone with auditory white noise leads to redundancy gain when compared to presenting the auditory tone to the left and right ear only. Interestingly, using normal participants, the experimenters were able to show small but significant violations of the race model within the auditory modality, particularly at the 15th percentile of the cumulative distribution of reaction times. As a point of clarity, using two tones for the redundant trial did not cause a violation of the race model, the authors suggested that these tones unified and hence were not perceived as two stimuli. Hence the redundancy trial was composed of a tone and white noise as mentioned above. This is currently the only study working with purely auditory information in the redundancy paradigm.

With the exception of these two studies, the advancement of the understanding of the phenomena (especially in neurological normal populations) is stagnant. There are several different methods for conducting a redundancy gain paradigm, in particular the task can be constrained to only the visual system (e.g Corballis, 1998, 2002; Miller 2007a, 2007b, Miller and Adams, 2006, Miller and van Nes, 2007), the auditory system (Schroter, Ulrich, and Miller, 2007), and in both the auditory and visual domain (e.g.

Miller, 1982, 1986, 1991). Interestingly, other than perhaps the combined visual and auditory paradigm, there is no clear pattern of race model violations in the visual paradigm, and the auditory paradigm only showed one small, slight violation. The inconsistency of results suggests the need for a large, comprehensive study looking at how the results for the different redundancy gain paradigms are similar and different. Additionally, there, as of this date, has not been a single study that has used the same set of participants for evaluating all three basic sensory redundancy gain paradigms. Working with the same participants can afford for running a correlation analysis, to understand how similarly participants perform across task and to what degree the tasks utilize the same underlying mechanism of activation and response.

In general the following study focuses on addressing the following questions in a participant group, all of whom are evaluated in all three sensory paradigms.

1. How participants are distributed around the boundary conditions of the race model?

   Hypothesis 1. The distribution of results will show that participants fall around the boundary conditions of the race model for each of the different redundancy gain tasks.

2. Do individuals violate the race model but are masked in the overall analysis?

   Hypothesis 2. Given the assertion in Hypothesis 1, if a particular redundancy gain task does not show violations of the race model, then it is likely that either the magnitudes of violations are small compared to those participants that do not violate, or the number of individuals who violate are disproportionate to those not violating.

3. To what extent are the visual, auditory, and visual-auditory redundancy gain reaction times correlated?

   Hypothesis 3. If the redundant effect is conserved across modalities, there should be a strong correlation between all the redundancy gain paradigms.

4. To what extent are differences from the race model boundaries correlated and what are the implications for significant violations of the race model?

   Hypothesis 4. If the mechanism of violations of the race model is conserved between sensory modalities there should be strong correlation in the measure race-model violations. In other words, those showing violation in the visual redundancy gain paradigm should also show it in the auditory and visual auditory paradigms.

To evaluate these questions participants were tested with a visual, auditory, and visual and auditory redundancy gain paradigms, designated as experiments 1, 2, and 3 respectively. The data was tested with the race model inequality, as well as analyzed on an individual by individual basis with respect to the race model for correlation and evaluation of reaction time distributions. For the sake of clarity, the experimental methods, results, and discussion will be covered initially as independent entities. However, this will be followed by a general discussion that details the correlation and factor analysis work that integrates all three experiments into a coherent picture of redundancy gain.

CHAPTER 2

EXPERIMENT 1: VISUAL REDUNDANCY GAIN

Since all of the redundancy gain tasks involve the same framework and participants the general information across these experiments is provided below.

A total of 76 participants were included in the study (47% female & 53% male). All participants were recruited from the undergraduate population at Georgia Institute of Technology, were screened to have normal or corrected to normal vision and hearing and had no history of debilitating neurological, otological, or ophthalmologic disorder. Participants ranged in age from 18-24 (mean age of 20 years) with nearly all participants being right hand dominant (89% right, 11% left). All participants provided written consent, approved by the Institutional Review Board at the Georgia Institute of Technology, to participate in the study.

Participants had one 45 minute experimental session that included three redundancy gain paradigms and one visual memory task. The order of presentation of the four paradigms was counterbalanced and randomized amongst participants to ensure there were no ordering effects. The redundancy gain paradigms all utilized the general framework of stimuli presentation in including the same stimulus onset asynchronies (300,500, and 700 ms), same visual stimulus of a white square (each side measuring ~1 degree of visual angle), and the same auditory tone (700 Hz), all presented for a duration of 300 ms. For each redundancy gain experiment there was a total of 180 trials, with 60 trials in each of the two unilateral conditions and 60 trials in the redundant condition.

Methods

The visual stimuli were presented on a cathode ray tube (CRT) screen driven by a Pentium 4 personal computer (PC) using the Presentation software package (Neurobehavioral Systems, Albany, NY, USA) . The stimuli consisted of white square (~1degree of visual angle) presented either 5 degrees of visual angle to the right or left of fixation (red square, 1/3 degree of visual angle), or bilaterally (for a total of three visual stimuli configurations). The participants were asked to maintain fixation on the red square, which disappeared to cue the upcoming stimuli presentation (300 ms duration). The interval from the disappearance of the fixation cross to the appearance of the stimuli varied randomly between 300, 500, or 700 ms. There was a total of 20 presentations of each of the 9 conditions (3 SOA x 3 Visual Stimuli), leading to 180 trials total. All the participants were instructed to respond as quickly as possible with a left mouse click as soon as the target stimuli appeared.

Analysis/Results

Redundancy Gain and Race Model Violations

Ulrich, Miller, & Schroter (2007) provided an algorithm for the analysis of reaction time data in a redundancy gain task, particularly looking at whether the race model was violated. The program is designed to test the overall race model for the entire sample evaluated and provide an overall test for the violation of the race model. For race model analysis, a cumulative distribution function (CDF) with a total of 10 percentages values (deciles) ranging from 0.05-0.095 was created. In order to evaluate whether there was significant redundancy gain, pairwise T-tests were conducted for each decile across the participants. In order to be conservative, the fastest reaction time for the non-redundant condition was selected for comparison to the redundant condition. The results for the visual paradigm are listed in Table 1.

Table 1 Visual Redundancy Gain

Decile	Δ Mean (ms)	t-score	Significance (p)
0.05	-0.36	-0.23	0.816
0.15	4.55	5.23	<0.001
0.25	6.26	8.52	<0.001
0.35	7.47	8.23	<0.001
0.45	8.98	8.49	<0.001
0.55	9.15	8	<0.001
0.65	8.86	6.14	<0.001
0.75	11.61	7.48	<0.001
0.85	10.16	4.04	<0.001
0.95	-4.14	-0.74	0.469

There is clearly evidence for significant redundancy gain within the visual redundancy paradigm for the decile 0.15-0.85, with a magnitude range from 4.6 ms to 11.6ms, which is on the order of the redundancy gain reported by controls participants in Corballis (1998), Roser and Corballis (2002) and participants in Corballis (2002). Interestingly, the magnitudes were much smaller than those reported by Miller and Adams (2006), Miller (2007), and Miller and van Nes (2007).

Despite the presence of redundancy gain, there were no significant violations of the race model within the visual redundancy condition. The estimated CDF showing the 10 percentiles generated by the Ulrich, Miller, & Schroter (2007) algorithm are presented in Table 2.

Table 2 Visual Race Model Evaluation					
Decile	**Left**	**Right**	**Redundant**	**RM Boundary**	**t-Value**
0.05	193.35	189.74	186.2	179.05	-4.459
0.15	214.99	211.06	203.7	198.98	-4.516
0.25	227.66	223.41	214.13	208.8	-5.792
0.35	238.56	233.24	223.11	215.86	-8.05
0.45	249.52	243.44	231.49	222.29	-8.495
0.55	261.42	254.96	242.59	227.71	-11.229
0.65	275.26	268.12	255.7	232.9	-11.985
0.75	294.57	285.06	269.45	237.96	-13.029
0.85	323.86	312.1	297.55	243.35	-13.028
0.95	396.37	382.64	370.74	249.18	-16.076

The lack of a violation of the race model parallels the results of Corballis (1998, 2002) and Roser and Corballis (2002), while the results shown here are inconsistent with the results reported by Miller and Adams (2006), Miller and van Nes (2007), and Miller (2007). This discrepancy, plus the gaining a better understanding of the estimated CDF, requires an exploration of the dynamics of the analysis of the data in the context of the race model inequality.

Exploring the Race Model

Looking at the overall results generated by the Ulrich, Miller, & Schroter (2007) algorithm provided a very broad perspective of thousands of data points. In order to explore the data on a more individual basis, the estimated CDF for each individual in this study was used to calculate violations of the race model at each decile by subtracting the redundant reaction time from the race model boundary condition (leading to negative values indicating a violation). Of the 76 participants 42 (approximately 55%) of them showed violations of the race model for at least one decile. In other words, a majority of participants showed a race model violation, which is a surprising finding given the lack of a significant race model violation in the overall results of the analysis.

In order to understand the discrepancy it is necessary to look at how the violations of the race model fall with respect to the deciles to assess whether there is consistency within and across a decile. Table 3 shows that the violations of the race model are not conserved within a single decile but are instead distributed across 5 deciles, with the highest number of violations occurring at 0.15, which amounted to nearly 33% of the participants showing a violation.

Table 3 **Distribution of Race Model Violations in the Visual Redundancy Gain Paradigm**

Decile	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
Violating	21	25	20	13	10	3	2	1	0	0

Furthermore, the discrepancy can be further explained by looking at the distribution of race model violations (difference between the reaction time for redundancy and race model boundary) for each decile, across all participants, as shown in Figure 1.

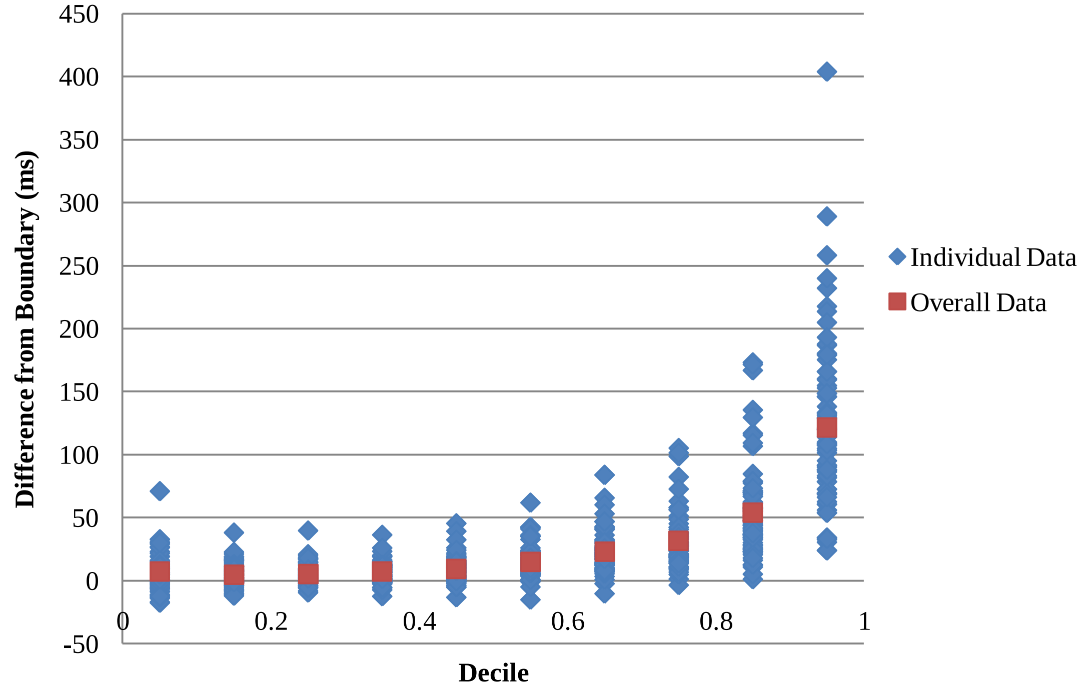

Figure 1 Visual Race Model Violation Distribution

Reviewing Figure 1, it is apparent that the earliest deciles show a relatively smaller difference between the redundancy conditions reaction time and the boundary set by the race model inequality, though the majority of differences are greater than zero. This corresponds with the fact that the lower deciles also had the highest number of race model violations on an individual basis. Furthermore, it corroborates the general pattern seen in the work of Corballis (1998, 2002) and Roser and Corballis (2002). It should also be noted that Miller (2007) found significant violations of the race model with his redundant visual paradigm along only the lower percentiles, particularly the 7.5, 17.5, 22.5 and 27.5 percentiles. Additionally, Miller and Adams (2006) and Miller and van Nes (2007) also showed violations of the race model using a similar visual redundancy paradigm.

Discussion

Considering only the visual redundancy paradigm, it is apparent that the results presented here fall in line with those of previous work (Corballis, 1998, 2002, Roser and Corballis, 2002). With respect to the work of Miller (2007), there is no immediately apparent reason why the visual redundancy task he used should differ than those of this or previous work. The visual stimuli he used were white squares with a side of 2.2 degrees of visual angle presented at an eccentricity of 3 degrees of visual angle. In effect, his stimuli covered nearly 5 times the area and were three-fifths as far away from the central point when compared to the white squares utilized in this study. Reviewing the paradigms used by Corballis (1998, 2002) and Roser and Corballis (2002), it appears that their stimuli were much nearer to those used for this study. Their task used circular disks with a diameter of 0.86 degrees of visual angle, displayed at an eccentricity of 5 degrees or 2.5 degrees. With regard to the stimuli, Miller (2007) used a much larger visual target. There were also two other major procedural differences in terms of the stimuli presentation and participant response. In this study and those conducted by Corballis (1998, 2002) and Roser and Corballis (2002) there were different SOAs in an attempt to mitigate anticipatory response, whereas Miller (2007) used a fixed SOA from the warning signal before the presentation of the stimuli. Furthermore, Miller (2007) was concerned with differences in reaction times when responding with the left, right, or both hands. The experimental condition that most closely related to the one presented here involved the participants responding with both hands simultaneously to the all of the visual stimuli conditions. Interestingly, Miller and Adams (2006) and Miller and van Nes (2007) showed that responding with both hands lead to violations of the race model in a visual only paradigm. Importantly, there were no violations of the race model when responding with a single hand. While that results seem to at least perhaps explain the difference, the other two factors might contribute to a difference in the whether the race model is violated. Since both facets can be empirically tested a potential future study should focus on each, with systematic variation of the size of the visual stimuli and conditions with and without variations in the SOA.

CHAPTER 3

EXPERIMENT 2: AUDITORY REDUNDANCY GAIN

Methods

The auditory redundancy gain stimuli were based on the work by Schroter, Ulrich, and Miller (2007). Specifically, the participant heard a 700 Hz tone played in either the right or left ear, or a 700 Hz tone played in the left ear and white noise played in the right ear, or vice versa. Like the visual redundancy task, the participants were told to fixate on a center red square and the disappearance of the square cued the participant that a stimuli was about to appear. As in the visual only task, SOAs were randomly selected between 300, 500, and 700 ms, with the duration of the auditory stimulus itself lasting 300 ms. Also, in parallel to the visual redundancy gain paradigm, there was a total of 20 presentations of each of the 9 conditions (3 SOA x 3 Auditory Stimuli), for a total of 180 trials. Likewise the participants were instructed to respond as quickly as possible with the left mouse click at the occurrence of the auditory stimulus.

Data Analysis/Results

Redundancy Gain and Race Model Violations

Like the visual redundancy gain task, the auditory redundancy gain task was processed by the algorithm described by Ulrich, Miller, & Schroter (2007) in an analogous manner. The test for auditory redundancy gain was analogous to that described in the visual redundancy gain section and for brevity will not be reiterated. The results of the analysis are presented in Table 4.

Table 4. Auditory Redundancy Gain			
Decile	**Δ Mean (ms)**	**t-score**	**Significance (p)**
0.05	4.46	3.48	<0.005
0.15	6.91	4.12	<0.005
0.25	8.82	5.62	<0.005
0.35	10.79	7.18	<0.005
0.45	11.58	7.29	<0.005
0.55	12.48	6.94	<0.005
0.65	12.86	6.03	<0.005
0.75	13.33	5.39	<0.005
0.85	12.44	3.66	<0.005
0.95	5.63	0.77	0.442

As with the visual redundancy gain task, the auditory redundancy gain task showed significant redundancy gain across several deciles (0.05-0.85). The magnitude of the differences between the single and redundant auditory conditions ranged from 4.5 to13.3 ms, which matched quite closely to results of Schroter, Ulrich, and Miller (2007).

In contrast to the work of Schroter, Ulrich, and Miller (2007), there were no significant violations of the race model across any decile of the auditory redundancy gain data. The estimated CDF showing the 10 percentiles generated by the Ulrich, Miller, & Schroter (2007) algorithm are presented in Table 5.

Table 5 Auditory Redundancy Gain Race Model Violations					
Decile	**Left**	**Right**	**Redundant**	**RM Bound**	**t-Value**
0.05	158.12	159.93	149.9	150.39	0.393
0.15	175.64	175.76	165.03	164.2	-0.485
0.25	188.68	188.22	175.89	171.85	-1.871
0.35	199.82	198.53	184.8	179.38	-2.728
0.45	210.8	208.78	194.24	185.31	-3.989
0.55	223.56	220.59	204.54	190.99	-5.58
0.65	239.43	235.69	217.59	196.35	-7.243
0.75	261.01	254.33	235.05	201.57	-8.614
0.85	293.72	287.54	265.45	206.86	-10.443
0.95	366.99	377.51	336.99	212.59	-14.551

Interestingly, Schroter, Ulrich, and Miller (2007) reported a slight but significant violation of the race model at the 0.15 decile, using a very similar paradigm as the one utilized here; however, there is no evident replication of such a result in this dataset.

Exploring the Race Model

As with the visual condition, the general analysis of the data does not capture the entire scope or implications of the data from 76 participants. The number of participants violating the race model for at least on decile for the auditory condition was 68 or nearly 90% of the participants. The breakdown of race model violators for the auditory redundancy gain condition is shown in Table 6.

Table 6 Distribution of Race Model Violations in the Auditory Redundancy Gain Paradigm

Decile	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
Violating	49	43	36	31	24	16	7	2	0	0

The more comprehensive plot of the difference between the redundant auditory condition and the race model boundary is presented in Figure 2.

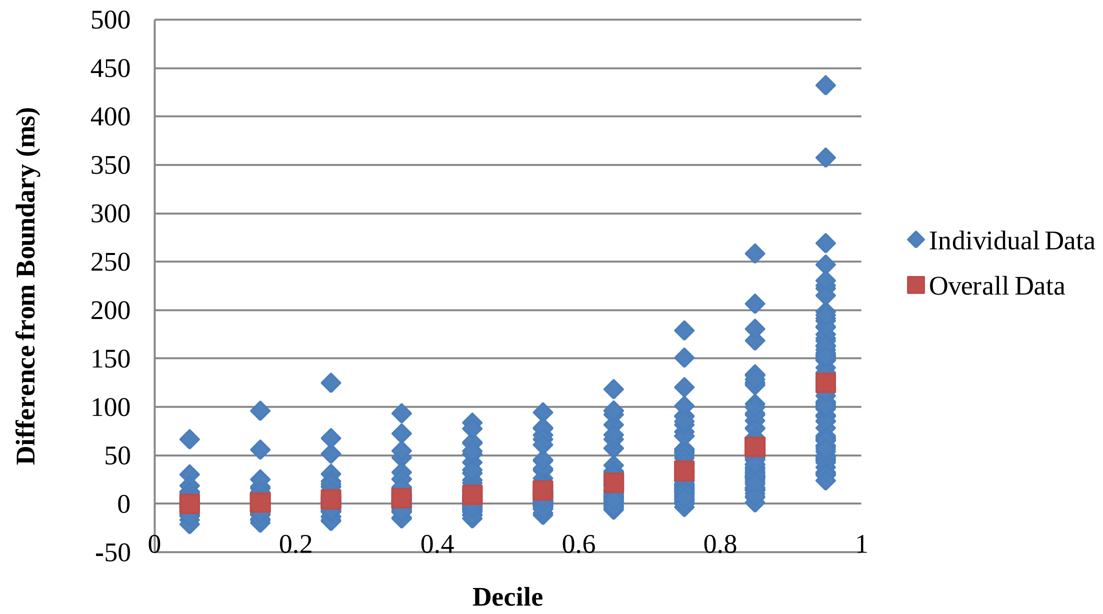

Figure 2 Auditory Race Model Violation Distribution

The pattern shown in Figure 2 is very similar to the one shown in Figure 1 for the visual redundancy gain condition, with the lower decile having smaller differences between the redundant condition and the boundary condition. In fact, the 0.05 percentile shows an overall violation of the race model, though it is not significant. At least in principle, if not statistically, the pattern follows the results of Schroter, Ulrich, and Miller (2007) who showed that the 15th decile significantly violated the race model, and the 5th and 25th were close to significantly violating the race model.

Discussion

Given that there is only one previous study focusing on an auditory redundancy gain paradigm, it is necessary to be tentative about points of inconsistency between the data sets. It should be noted that the auditory stimuli used for this study were designed to be analogous to those used by Schroter, Ulrich, and Miller (2007). However, despites the attempt to replicate the study exactly, minor modifications were necessary for internal consistency across the different redundancy gain paradigms.. In particular, Schroter, Ulrich, and Miller (2007) did not have different SOAs, instead they corrected for anticipatory responses by excluding reaction times less than 80ms. While this certainly could lead to divergent distributions of reaction times, it should be noted that there was only data from 20 participants, which when combined with the fact that the violation of the race model was slight and in one decile, there might be the possibility of Type I Error, if there was not enough power.

CHAPTER 4

EXPERIMENT 3: VISUAL AND AUDITORY REDUNDANCY GAIN

Methods

The combined auditory and visual task is structured in parallel to the previous two redundancy gain tasks. The stimuli were composed of white square (1 degree of visual angle) presented at the center, a 700 Hz auditory tone presented binaurally, or the simultaneous presentation of both the white square and 700 Hz tone. Like the other redundancy tasks, the participants were told to fixate on a center red square and the disappearance of the square cued the participant that a stimuli was about to appear. Likewise SOAs were randomly selected between 300, 500, and 700 ms, with the duration of the visual and/or auditory stimulus themselves lasting 300 ms. Again, there was a total of 20 presentations of each of the 9 conditions (3 SOA x 3 Visual-Auditory Stimuli), for a total of 180 trials. Likewise the participants were instructed to respond as quickly as possible with the left mouse click at the occurrence of the auditory and/or visual stimulus.

Data Analysis/Results

Redundancy Gain and Race Model Violations

Paralleling the analysis of the auditory and visual redundancy gain conditions, Table 7 shows the redundancy gain analysis for the visual-auditory redundancy gain condition.

Table 7 Visual-Auditory Redundancy Gain			
Decile	**Δ Mean (ms)**	**t-score**	**Significance (p)**
0.05	4.02	2.34	<0.05
0.15	9.36	4.87	<0.005
0.25	14.91	7.21	<0.005
0.35	20.17	8.66	<0.005
0.45	26.81	10.16	<0.005
0.55	35.31	11.43	<0.005
0.65	44.45	12.83	<0.005
0.75	58.06	14.43	<0.005
0.85	74.93	16.51	<0.005
0.95	93.94	14.93	<0.005

Reviewing the results it is apparent that all deciles showed significant redundancy gain for the visual-auditory condition. The magnitude of differences between the redundant and race model boundary condition varied from 4 ms to 94 ms, which is in close agreement with the values obtained by Miller (1982, 1986, & 1991) in his original race model inequality work using a visual-auditory redundancy gain paradigm to suggest the race model was an inadequate explanation of the redundant gain.

In addition to the significant redundancy gain, there were also several deciles where the redundancy gain violated the race model significantly. The results of the race model analysis are presented in Table 8.

Table 8. Visual-Auditory Race Model Violations					
Decile	**Visual**	**Auditory**	**Redundant**	**RM Bound**	**t-Value**
0.05	195.26	161.27	154.09	156.75	1.547
0.15	218.64	181.68	169.89	175.48	3.59*
0.25	233.47	197.17	179.9	188.4	5.721*
0.35	247.21	211.75	189.27	198.93	6.236*
0.45	261.16	227.71	197.4	208.61	6.451*
0.55	277.19	246.84	206.23	216.58	6.315*
0.65	296.9	269.62	217.04	225.22	4.572*
0.75	324.45	305.16	233.26	233.05	-0.076
0.85	366.41	350.23	257.31	241.36	-3.673
0.95	446.19	432.69	313.41	249.72	-9.092

* Denotes $p < 0.05$

Reviewing Table 8, there were six deciles with significant violations of the race model, from 0.15 to 0.65, with 0.05 approaching significance. These results correspond closely to Miller's (1982) original work which showed significant violations for the 0.15 through 0.35 percentiles, and near significant violations at the 0.05 and 0.45 points and also his follow-up work utilizing the visual-auditory paradigm (1986,1991). Additionally, the result match very close with the younger adult control group that Bucur, Allen, Snaders, Ruthruff and Murphy (2005) reported when looking at the redundancy gain in older adults. They found significant violation in the race model in 8 out of the 10 percentiles, 0.05 to 0.85.

Exploring the Race Model

As a point of comparison, there were 71 of the 76 participants who showed violations of the race model, or just less than 94% of the participants. The breakdown of the race model violators is presented in Table 9.

Table 9 Distribution of Race Model Violations in the Visual-Auditory Redundancy Gain Paradigm

Decile	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
Violating	44	55	60	60	64	62	60	47	22	3

Reviewing the table shows that there are substantially more violators of the race model per decile and across more deciles, when compared to the auditory or visual redundancy gain results.

Furthermore, the plot of the difference between the redundant reaction time and the race model boundary is shown in Figure 3.

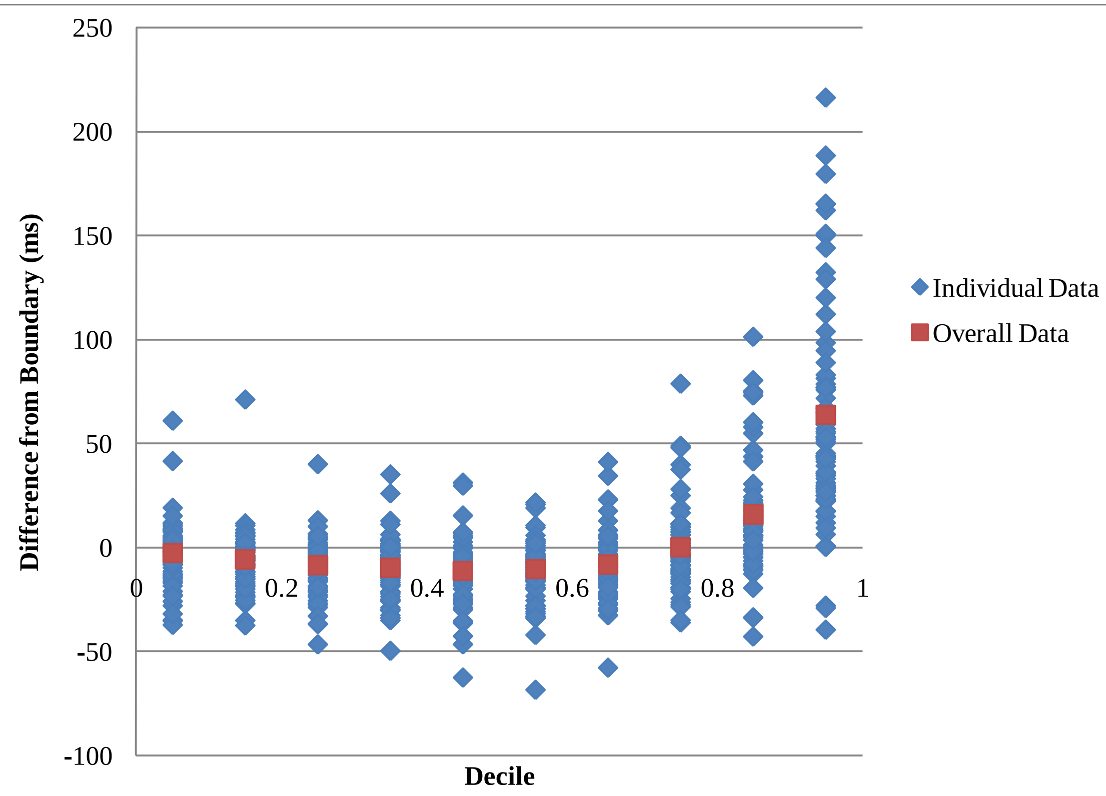

Figure 3 Visual-Auditory Race Model Violation Distribution

Relative to Figure 1 and 2, Figure 3 shows very clearly a distribution of differences lies well below the zero point, indicating violations of the race model.

However it should be noted that the same pattern of increasing differences between the redundant reaction time and race model boundary occur with the increasing percentile.

Discussion

Interestingly despite variations in stimuli presentation and differences in experimenter procedures, it appears the pattern of redundancy gain and violations of the race model are very robust and consistent. For example, both Miller (1982, 1986) and Bucur, Allen, Sanders, Ruthruff and Murphy (2005) used an asterisk/plus sign as a visual cue and a 780 Hz and 1000 Hz tone as the auditory target, respectively. Whereas described above the visual cue was a white square with an approximate side length of one degree of visual angle and the auditory target was a 700 Hz tone. Furthermore, neither Miller (1982) nor Bucur and colleagues (2005) had variations in their synchrony of onset, whereas 3 different SOAs were used in the task for this experiment. Overall, it should be clear that there is uniqueness about the redundant effect found when combining two different sensory modalities. Miller (1986) manipulated the synchronies of the auditory and visual information and found that a visual stimulus presented after an auditory stimulus has little effect on the redundant effect. Additionally, Miller (1986) found that the auditory stimulus presented long after the visual stimulus could affect the redundant effect. Finally, Miller (1986) found that when presented simultaneously, the redundancy gain effect was relatively smaller (as opposed to when the visual information was presented ahead of the auditory stimulus, 33 – 167 ms) suggesting the auditory stimulus was driving the effect before the visual cue could have an effect. The highest redundancy gain effect was about 100 ms, which was about the difference between the mean reaction time to the auditory stimulus and visual stimulus. Perhaps highlighting a potential explanation of the consistent violation of the race model in the visual and auditory paradigm, Miller (1991) showed that congruent visual and auditory stimuli (e.g. high frequency tone paired with a square high on the screen) had higher redundancy gain effects with violations of the race model as compared to those that were not congruent (e.g. low frequency tone paired with square high on screen), perhaps suggesting that the processing of the visual and auditory stimuli involves an attempt to bind them into one stimulus.

CHAPTER 5

EXPERIMENT 4: VISUAL WORKING MEMORY TASK

The work presented here is expected to be a component of a large series of studies, including imaging studies investigation the integrity of the corpus callosum. These studies involve building a comprehensive database of participants, including measure beyond redundancy gain. While Experiment 4 may not fit logically into the work presented here, it is essential for the follow up research using the participants in the present study. The visual working memory task was selected as a potential correlate to the integrity of the anterior commissure, which is relevant for future imaging work looking at the integrity of the corpus callosum. However, since the data was being collected, it was analyzed with respect to the redundancy gain findings and has been integrated into the general discussion of the three redundancy gain paradigms. Presented below is the methodology of the visual working memory task.

Methods

The visual working memory task is modeled after an experiment performed by Reuter-Lorenz and colleagues (2000) to show changes in memory performance with an aging brain. For the task, the participants were asked to maintain fixation on a central red square, after 500 ms four upper case consonants (randomly selected from the alphabet and excluding 'y' because of its ambiguous standing as a consonant/vowel) were presented in the four quadrants, either one degree above or below the horizontal meridian and one degree to the left or right of the vertical meridian, these four letter remain on for 500ms. The four letter presentation is followed by 2.5 seconds of fixation then the replacement of the fixation square by a lower case letter lasting 500 ms. The lower case letter either corresponded or did not correspond to one of the original four letters and was followed by a 2.5 second duration for the participant to respond. The participant was required to respond with a left mouse click, using their right hand, if the lower case letters was one of the originally presented four, or a right mouse click if the letter was not one of the originally presented four. There were a total of 10 practice trials with feedback (in order to ensure that the participants were familiar with and practiced on the task) followed by 96 trials, evenly split between the letter being present in the original four and the letter being absent.

Results

Overall, the performance on the visual working memory task averaged 93.6%. The lowest accuracy (A) was just at 77.1%, whereas the highest performance was 100% accuracy. A breakdown in accuracy is provided in Table 10, which clearly shows that over 81% of the participants have accuracies greater than 90%.

Table 10. Distributions of Accuracy Scores Placed into 5% Bins

Accuracy (A)	A ≥ 95%	95%>A≥90%	90%>A≥85%	85%>A≥80%	80%>A≥75%
# of Participants	29	33	11	2	1

Discussion

The average value of 93.6% presented here was lower than the accuracies reported by Reuter-Lorenz and colleagues (2000), as they showed near ceiling performance of 99%. However, their sample involved a total of 8 individuals as opposed to a total of 76 individuals presented here. Since the design of the experiment mirrors that conducted by Reuter-Lorenz and colleagues (2000), there is no apparent methodological reason for the difference in performance. The most plausible explanation is that with an increase in the number of participants, the sample studied included more variation in the accuracies.

CHAPTER 6

SUMMARY AND CORRELATION OF REDUNDANCY GAIN MEASURES

Recapitulation

While the results within each redundancy gain paradigm at first appear quite simple, there are some points of similarity and difference that should be explicitly summarized. For example, while there were no significant violations of the race model for the auditory only and visual only conditions, both showed over half of the participants violating the race model for at least one percentile (68 of the 76 and 42 of the 76, respectively). However, the visual-auditory condition, which did show significant violations of the race model in 6 of the 10 percentiles, had 71 of the 76 participants showing violations of the race model. The general pattern of results between these two conditions was apparent; the lowest decile had a higher reaction time than the next few deciles, followed by a much steeper increase in reaction times across the last percentiles. The same pattern was apparent in the visual-auditory conditions with significant violations of the race model in 6 of the 10 percentiles.

Exploring the pattern across the deciles more closely, looking over Figures 1, 2, and 3 it is apparent that they all follow the same general pattern. Again, the initial part of the distribution is slightly higher than the middle, which is then followed by an increase at the end of the distribution. Reviewing the graph for the visual condition, the redundancy gain paradigm that violates the race model the least also shows that most of the reaction times are tightly clustered. It also shows that along any one percentile, few data points are below zero, which implies that of the 42 participants who showed violations of the race models within at least one decile there was not one decile were most of the violations occurred (seen in Table 3). The same pattern holds true for the auditory condition, though there are clearly more values that are sub zero. Overall the data shows that 0.05 and 0.15 are around zero, or close to violating the race model and there is still the same pattern of variability in the violations of the race model across the decile (see Table 6). The visual-auditory graph clearly has the majority of the data points below zero, and the overall data falls below the zero line on seven of the ten decile. Further the visual-auditory graph has six significant violations of the race models (deciles 0.15-0.75, as listed above). It is apparent that the majority of data points in each decile are consistently below the zero line, which contrasts to both the visual and auditory conditions (see Table 9).

CDF and Race Model Boundaries

The visual-auditory data is particularly interesting and compelling. Within a sensory modality (visual or auditory only), there is not clear, robust, statistical evidence, for violations of the race model and, as a consequence, no evidence for the coactivation model. Between two sensory modalities, in this case the visual-auditory condition, there was clear, robust, statistical evidence for violations of the race model and hence strong evidence for the coactivation model. The implication is that there exists uniqueness to the coactivation pattern with two sensory modalities as opposed to just one sensory modality. In order to further explore this notion, the total estimated cumulative distributions used to generate the decile reports for each individual and the overall decile report were generated for each individual for each of the sensory conditions. Included are 3 of the 228 plots (Figures 4-6) which were selected as prototypical for consideration to highlight the differences between the different sensory conditions. Briefly, the graph shows the full model generated by the algorithm from Ulrich, Miller, & Schroter (2007, though the Matlab code was modified to return the values of the model as opposed to just the deciles presented), which includes an estimation of proportion for every second. Note that the boundary condition is determined by the sum of the left and right visual proportion for a given second, hence the full model shows the boundary approaching 2, which is the sum of the visual proportion and the auditory proportion. In most experiments, the focus is on the boundary condition up to 1, or the faster reactions times; however the full model is provided below for sake of completeness.

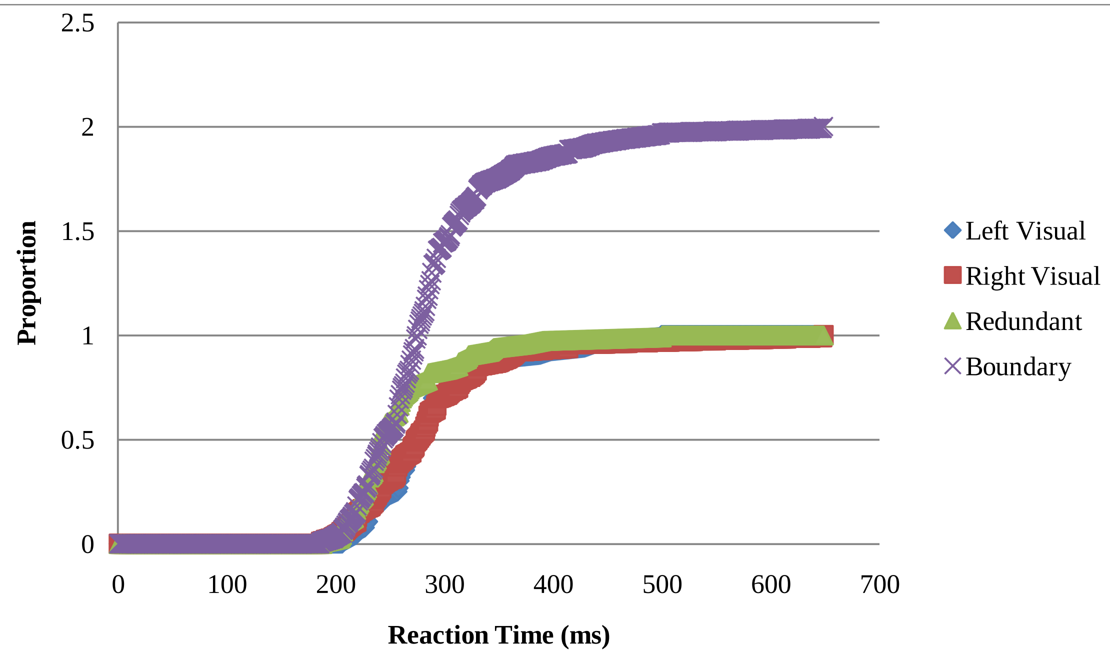

Figure 4 Participant 60 Visual Full Estimated CDF

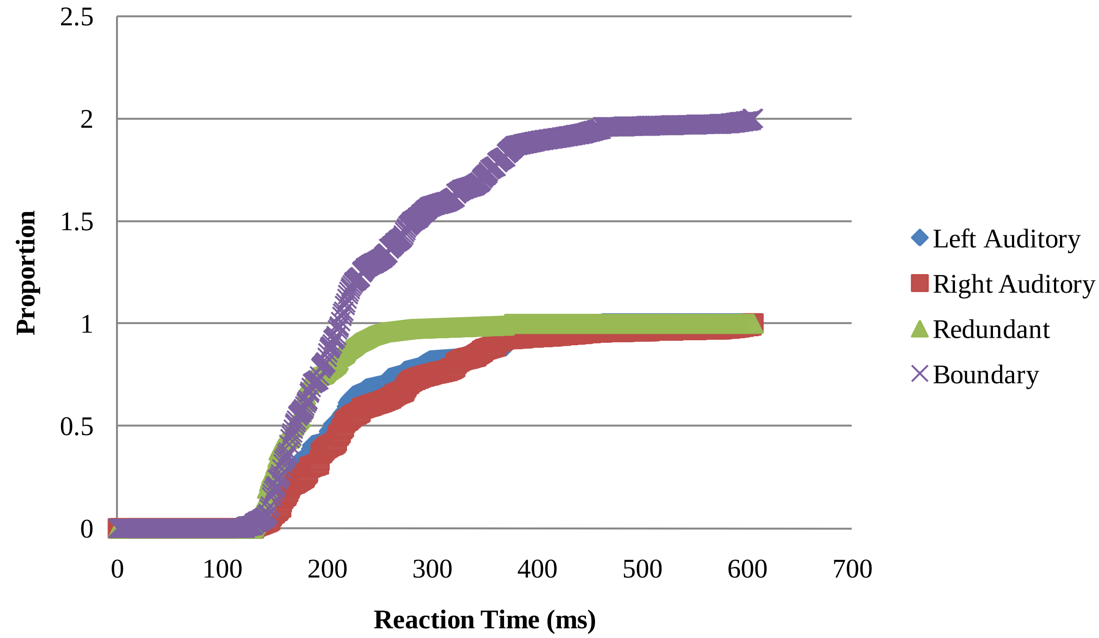

Figure 5 Participant 60 Auditory Full Estimated CDF

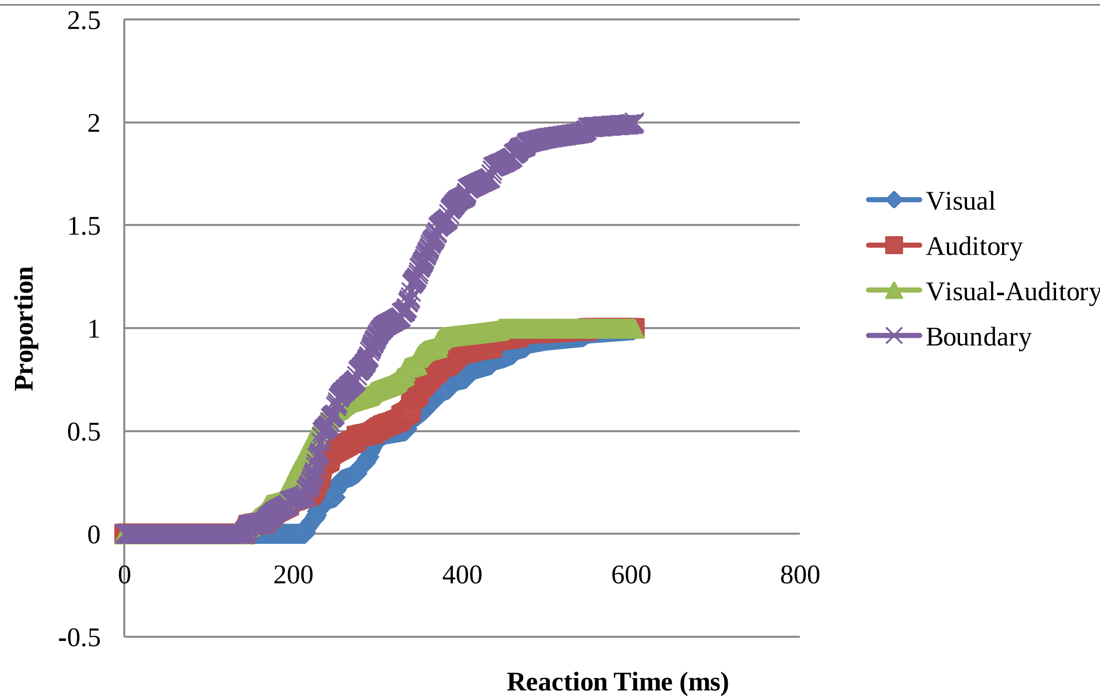

Figure 6 Participant 60 Visual-Auditory Full Estimated CDF

Reviewing the visual and the auditory graph it is apparent that the single stimulus nearly overlapped and had near equal contributions to the race model boundary (the sum of the two proportions at the respective decile). Additionally, the redundant reaction times fall in line or below the boundary (i.e expected from the statistical results). The pattern is starkly different for the visual-auditory condition; the visual reaction time distribution clearly lags the auditory reaction time distribution, making no or very little contribution to the race model boundary up until about 210 ms, when well over 0.5 of the proportion of reaction times have been accounted for in the model. Given this factor, it is not surprising that the initial deciles are dominated by the auditory reaction times. What is interesting, however, is the redundancy condition begins to show a violation of the race model before even the earliest visual reaction time.

Figure 7 shows the same data presented in Figure 6, though the focus is between the 100 and 250 ms mark.

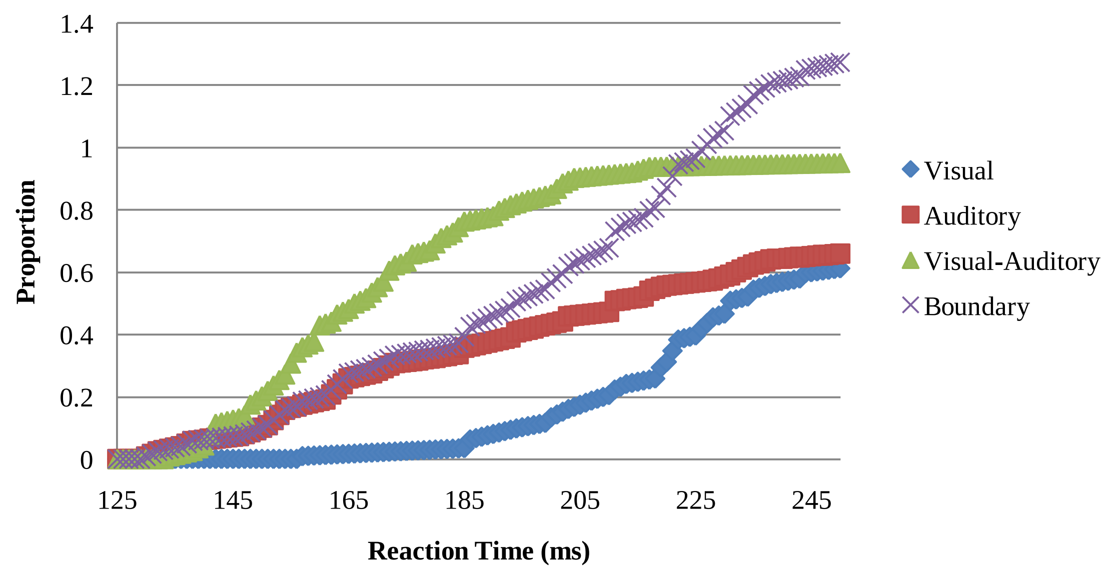

Figure 7 Visual-Auditory Partial Estimated CDF

Assessing the first 120 ms of the CDF more acutely shows the redundant condition exceeding the race model boundary despite the fact that there are no corresponding visual reaction times at that percentile. In the context of the coactivation model, it is possible that the visual information is generating activation that is contributing to the faster response, but that does not lead to response generation until much later with respect to the visual stimulus. This corresponds well with the results of Miller (1986), who showed that shifting the visual information to occur before the auditory information resulted in enhancement of redundancy gain. The result corresponds well with the idea that there is an accumulation of activation and by shifting the visual stimulus presentation, the activity generations align generating greater redundancy gain. At this point, there is no clear way to integrate this with the hemisphere coactivation model, since the model seems to make particular sense in the context of visual only information.

Another particularly interesting way to look at the data is to compare the differences between the redundant conditions to the boundary conditions at each decile, for each of the different redundancy gain tasks. For the sake of clarity, each difference scores within a decile and across the task were converted to z-scores and pairwise t-tests were conducted between each pair. The results are summarized in Figure 8 and Table 11. Notice in particular that the visual-auditory condition (as apparent from several graphs and tables above) separates from the visual-only and auditory-only conditions, with the differences being significant for nearly every decile (with the exception of the comparison between the auditory and visual auditory task in decile 0.05, $t(0.05) = 1.291$, $P = 0.201$). In other words, the differences between the visual-auditory redundant condition and race model boundary are significantly larger than those in either the visual-only or auditory-only condition. The visual-only and auditory-only condition, other than in the lowest two deciles, 0.05 and 0.15 were not significantly different (0.05, $t(75) = 4.487$, $p < 0.005$, 0.15, $t(75) = 2.291$, $p < 0.05$) suggesting that, like as presented above, the two single sensory modality conditions (Visual only and Auditory only) are similar with respect to redundancy gain measures. Overall, it appears that the different tasks, though similar in framework and effect, may be different in mechanism.

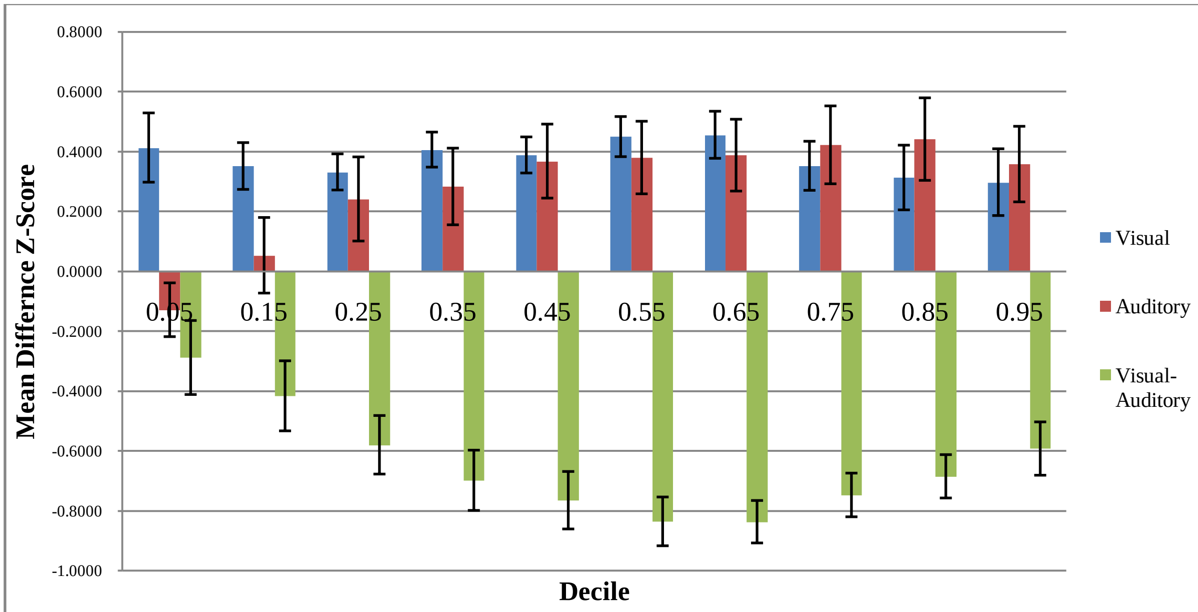

Figure 8. Comparison of Auditory, Visual, and Auditory Visual Redundant Condition-Race Model Boundary Differences

Table 11. Redundant Condition-Race Model Differences (Z-Scores)

	Decile 0.05			Decile 0.55†		
	Visual	**Auditory**	**Visual-Auditory ***	**Visual**	**Auditory**	**Visual-Auditory *,****
Mean Z-Score	0.4135	-0.1284	-0.2879	0.4501	0.3801	-0.8353
Std Error	0.1157	0.0898	0.1236	0.0670	0.1213	0.0815
	Decile 0.15			**Decile 0.65†**		
	Visual	**Auditory**	**Visual-Auditory *,****	**Visual**	**Auditory**	**Visual-Auditory *,****
Mean Z-Score	0.3519	0.0536	-0.4159	0.4562	0.3881	-0.8364
Std Error	0.0781	0.1262	0.1170	0.0787	0.1199	0.0709
	Decile 0.25†			**Decile 0.75†**		
	Visual	**Auditory**	**Visual-Auditory *,****	**Visual**	**Auditory**	**Visual-Auditory *,****
Mean Z-Score	0.3320	0.2417	-0.5795	0.3526	0.4225	-0.7470
Std Error	0.0603	0.1405	0.0978	0.0819	0.1301	0.0730
	Decile 0.35†			**Decile 0.85†**		
	Visual	**Auditory**	**Visual-Auditory *,****	**Visual**	**Auditory**	**Visual-Auditory *,****
Mean Z-Score	0.4066	0.2834	-0.6980	0.3134	0.4417	-0.6848
Std Error	0.0585	0.1280	0.1007	0.1081	0.1378	0.0724
	Decile 0.45†			**Decile 0.95†**		
	Visual	**Auditory**	**Visual-Auditory *,****	**Visual**	**Auditory**	**Visual-Auditory *,****
Mean Z-Score	0.3887	0.3682	-0.7647	0.2979	0.3583	-0.5921
Std Error	0.0603	0.1236	0.0960	0.1115	0.1262	0.0891

* Significantly Different from Visual Difference (P < 0.005

** Significantly Different from Auditory Difference (P< 0.005)

† Visual and Auditory Differences Not Significantly Different

Finally, in order to ensure that differences in reaction times between people are not accounting for any of the redundancy gain effects, a method reminiscent of Faust, Balota, Spieler, and Ferraro (1999) was conducted. Each participant had all their reaction times across the 9 redundancy gain conditions computed into Z-scores. For each individual the median values were selected across the 9 conditions and the mean of the two single stimulus conditions medians was calculated. The differences between the mean of the two median single stimulus and the redundant condition for each redundancy task was found. The difference scores were then placed in a one way ANOVA with the redundancy task as the condition and there was a significant effect ($F(2,225) = 137.56$, p

< 0.0005). Comparing the groups with pair-wise t-tests revealed that there were not significant differences between the difference score of the auditory and visual condition, but there was a significant difference between the visual and visual-auditory condition and the auditory and visual-auditory condition ($t(75) = -1.140$, $p = 0.258$, $t(75) = -16.32$, $p < 0.0005$, and $t(75) = -13.465$, $p < 0.0005$, respectively). Since this result was significant, it suggests that the same concerns presented by Faust, Balota, Spieler, and Ferraro (1999) are not of concern here and a regular analysis of reaction time differences is perfectly acceptable. Following the same analytical process with the exception of the Z transformation, the ANOVA was significant ($F(2,225) = 120.67$, $p < 0.0005$), with the same respective pair-wise comparisons showing the same patterns of significance ($t(75) = -0.692$, $p = 0.491$, $t(75) = -16.32$, $p < 0.0005$, and $t(75) = -13.465$, $p < 0.0005$, respectively). The data for both analyses are presented in Figures 9 and 10, respectively. Overall, the analyses presented highlights the similarity of the auditory and visual only tasks and also the stark difference of the visual-auditory task.

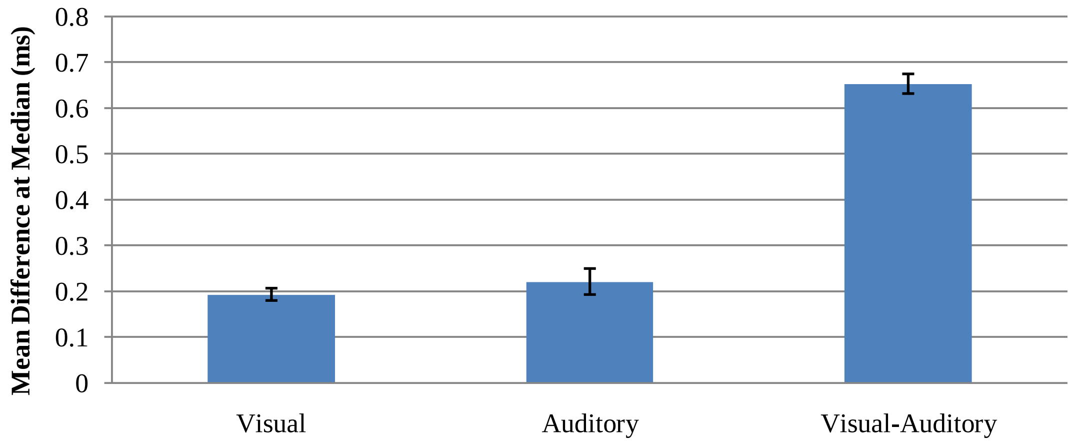

Figure 9. Mean of the Difference Score Between Redundant and Single Coniditions (Z-score)

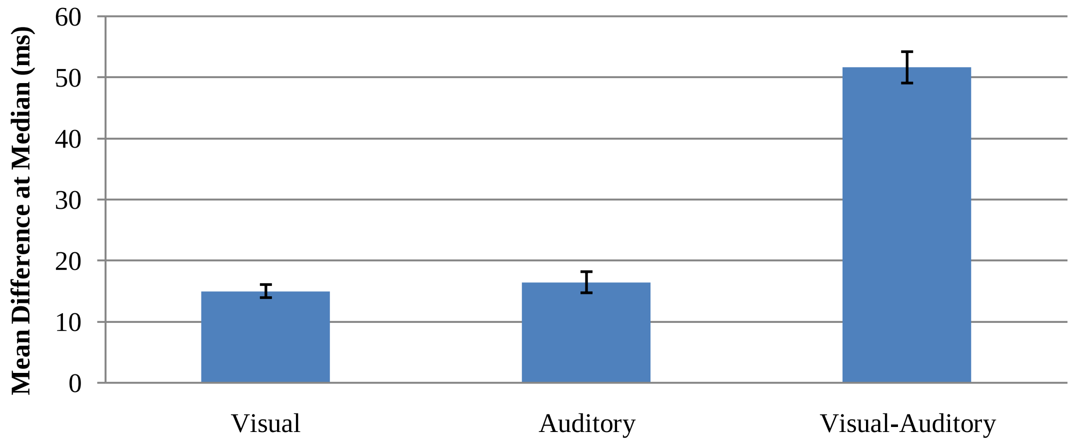

Figure 10. Mean of the Difference Score Between Redundant and Single Coniditions

Correlations of Auditory, Visual, and Visual-Auditory Redundancy Gain

Correlating the reaction times across the different redundancy gain paradigms for the 10 percentile points (0.0-0.95, incremented 0.10) of the CDF generated for each patient, the Pearson's correlation coefficient was 0.849 between the auditory and visual conditions, 0.896 between the visual and visual-auditory condition, and 0.893 between the auditory and visual-auditory condition, all of which were all statistically significant ($p<0.01$). A plot of the averages for each redundancy gain paradigm, across the 10 percentile points, is shown in Figure 11. Clearly, the reaction time distributions follow a very similar pattern as would be expected given the nature of the task. A more interesting question then, is to what extent are individual violations of the race model correlated across the different sensory redundancy conditions.

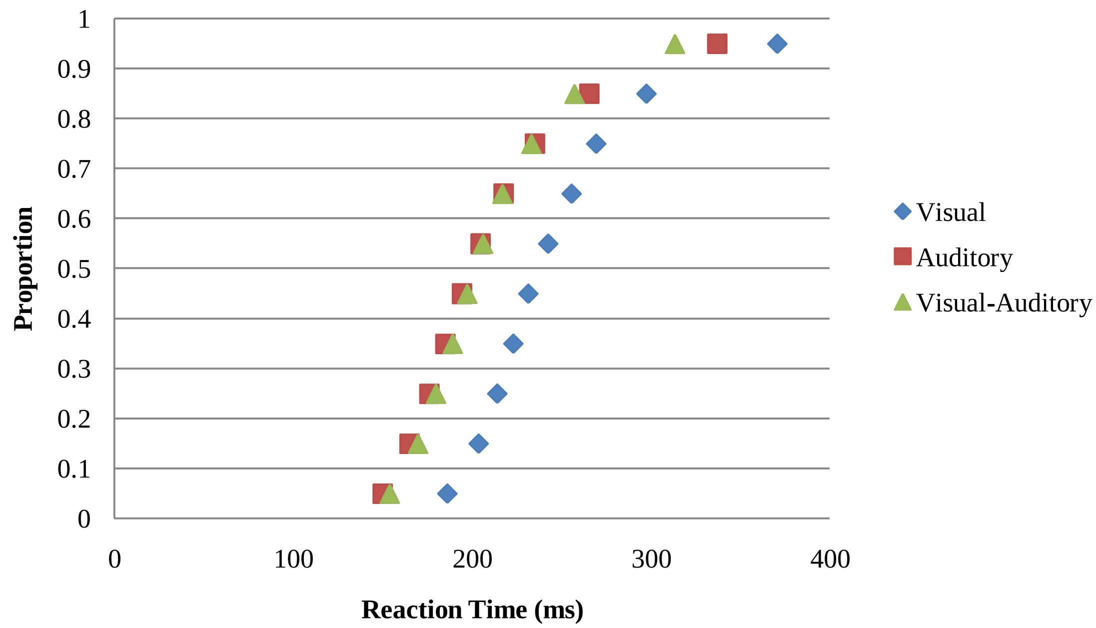

Figure 11. CDF Plots of the Overall Redundancy Reaction Time

The selection of criteria for the measure of central tendency of race model violations is not immediately apparent. The first major step was finding the difference of the reaction time and the redundant condition for each of the sensory conditions, across all deciles, and then selecting the appropriate measure of central tendency. The likelihood that there would be a repetition of a difference score within an individual is small; therefore, mode would not be a valid measure. The mean seems a tempting measure, however, there is some concern that the 0.95 percentile represents an outlier within each individual and may have a difference score that is not representative of the violation of the race model. Therefore, the median difference score was selected as an index for race model violation and as the measure to correlate across sensory conditions.

Correlating the race model violation index against the mean redundancy reaction times yields fairly robust correlation for the visual and auditory only indexes, but weak to medium correlations with the visual-auditory index, as shown in Table 11.

Table 12. Correlation Of Mean Reaction Times and RMVI

	Visual RMVI	Auditory RMVI	Visual-Auditory RMVI
Redundant Visual Mean	0.732**	0.639**	0.367**
Redundant Auditory Mean	0.672**	0.823**	0.279*
Redundant Visual-Auditory Mean	0.700**	0.703**	0.371**

** p < 0.01   * P < 0.05

Overall, the correlations suggest that if the index is lower (negative is a violation of the race model) then the reaction times are shorter, though the correlation is much stronger in the visual and auditory only conditions. Interestingly, the correlations with the visual-auditory RMVI and redundant mean reaction times show a weaker correlation. Suggesting, again, that the visual-auditory redundant tasks has a uniqueness apart from the visual only and auditory only tasks.

Correlating the RMVI across different redundancy gain tasks showed that the most tightly correlated were that visual and auditory conditions (0.538, p<0.001), the next highest correlation was between the visual and the visual-auditory conditions (0.312, p = 0.006), and a surprising near significant correlation of the auditory and visual-auditory conditions (0.211, p = 0.067). The scatter plots for each of the correlations are presented in Figure 10, 11, and 12 for the visual and auditory correlation, the visual and visual-auditory correlation, and the auditory and visual-auditory correlation, respectively.

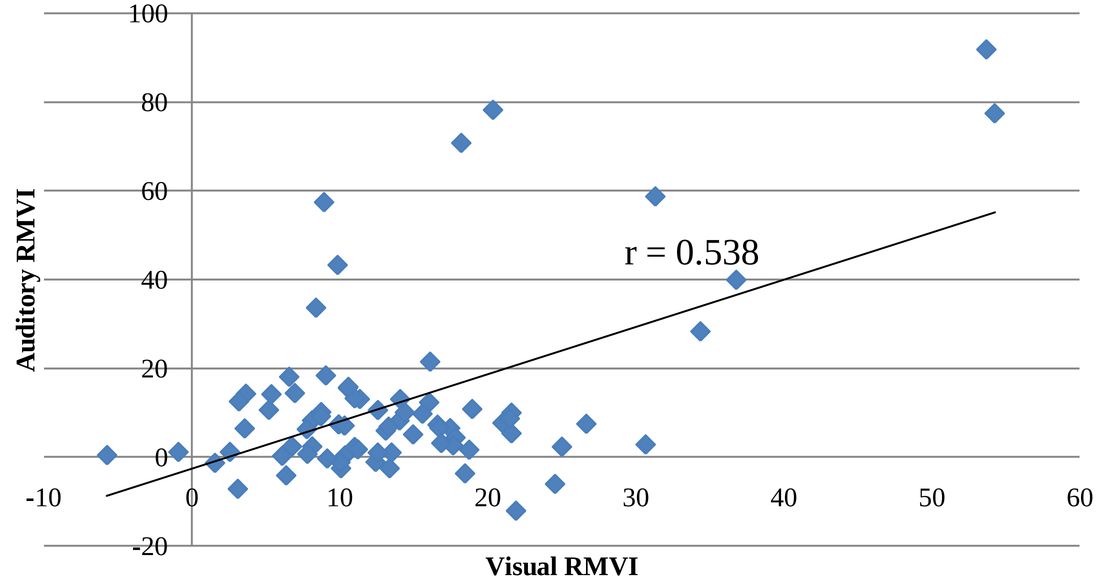

Figure 12. Visual RMVI and Auditory RMVI Correlation

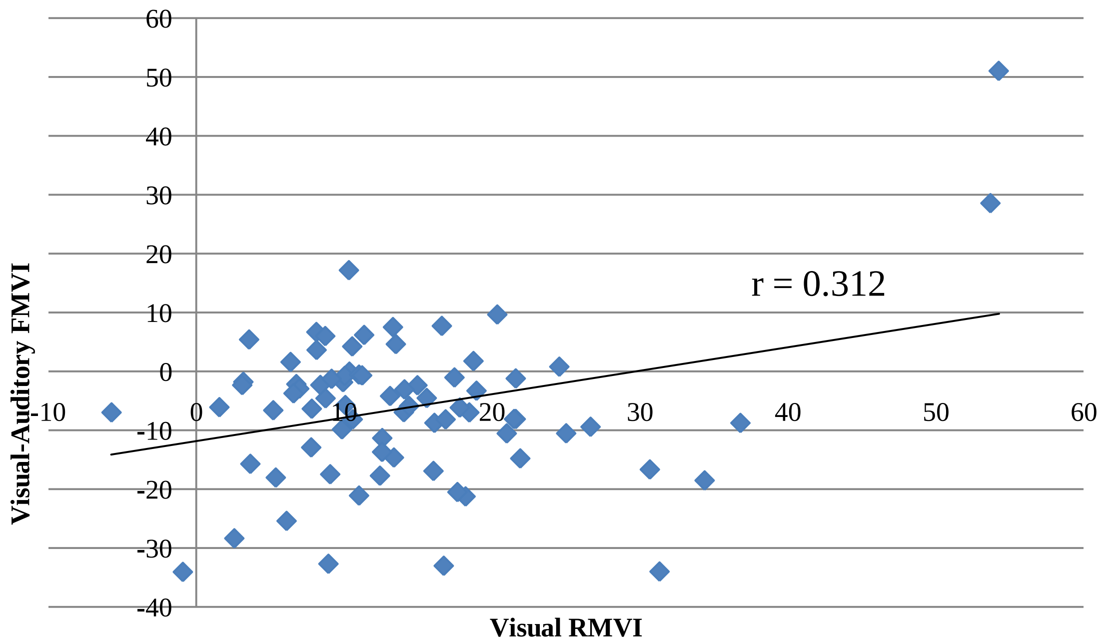

Figure 13. Visual RMVI and Visual-Auditory RMVI Correlation

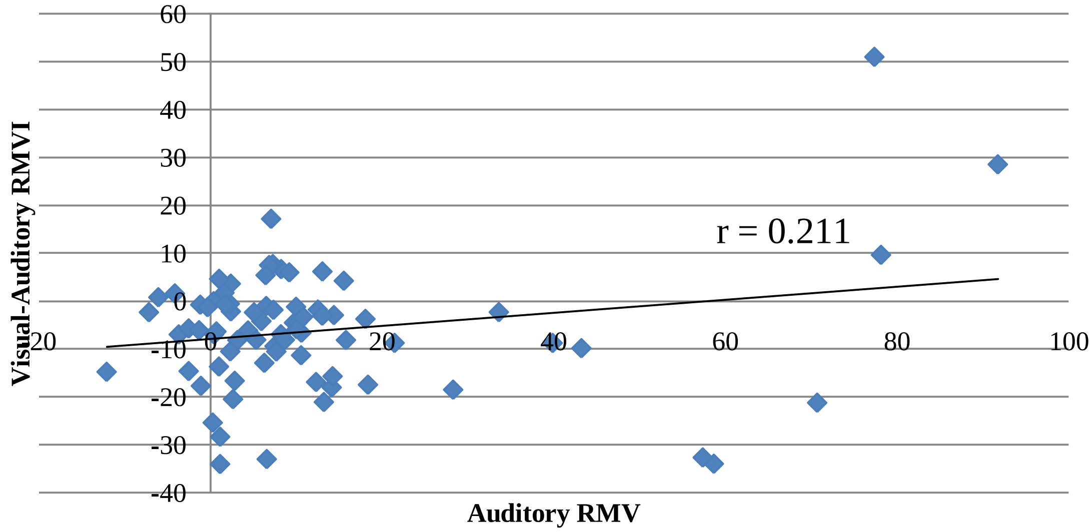

Figure 14. Auditory RMVI and Visual-Auditory RMVI Correlation

Looking at the RMVIs and correlating them to the visual memory working task revealed some interesting results. The visual condition was most strongly negatively correlated to the working memory task (-0.378, p=0.001), that is the higher the accuracy score the shorter the reaction times to visual tasks. The auditory condition also had a significant and negative correlation to the visual memory task (-0.276, p = 0.016). The visual-auditory difference scores were not significantly correlated to the visual memory task (-0.093, p = 0.463). Likewise, correlating mean redundancy reaction times to visual working memory accuracy also yields some interesting results. The only significant correlation was between the visual working memory accuracy and the visual-auditory mean reaction time ($r = -0.235$, $p < 0.05$). The next two correlations were the working memory accuracy and the visual mean redundancy reaction time ($r = -0.215$, $p = 0.069$) and the working memory accuracy and auditory redundancy mean reaction time ($r = -0.185$, $p = 0.110$).

CHAPTER 7

GENERAL DISCUSSION

Redundancy Gain & Violations of the Race Model

The work presented here is, to the best of the author's knowledge, the first study incorporating the different sensory variations of redundancy gain in one sample. As expected from previous independent studies, all modalities showed significant redundancy gain. The redundancy gain for the visual condition for each decile ranged from 5-13 ms, the auditory condition ranged from 4-12 ms, and the visual-auditory condition ranged from 4-93 ms. These values are reasonably consistent with those previously published (e.g Bucur, Allen, Snaders, Ruthruff and Murphy, 2005; Corballis, 1998, 2002; Roser & Corballis, 2002; Miller, 1982, 2007; Ulrich, Schroter, Miller, 2007).

Visual Redundancy Gain

The question of whether the reaction times corroborate or invalidate a race model is not as consistent across the different sensory conditions. Overall, neither the visual nor auditory conditions did show significant violations of the race model the visual-auditory condition did show violations of the race model. The fact that the visual condition did not show violations of the race model corroborates work using controls while testing split brain patients (who also show violations of the race model with visual stimuli). Despite the fact that there was not an overall significant violation of the race model, on an individual level there were 42 participants who violated the race model for at least one decile. These results coincide very nicely with the work of Corballis (2002), who showed that in a similar visual task with non-clinical participants there was not violation of the race model. Additionally, he reported that nearly half of the 58 participants show violation of the race model at some point of the reaction time distribution. As discussed above, several experiments conducted by Miller and associates have shown visual redundancy gain, though only under the condition where the participants were required to move their hands and/or respond with both hands. Importantly in conditions requiring a one handed response there were no significant violations of the race model (Miller, 2007a, 2007b, Miller and Adams, 2006; Miller and van Nes, 2007).

Auditory Redundancy Gain

The only study published on auditory redundancy gain (Schroter, Ulrich, and Miller, 2007), and the basis for the study design used here, showed not only redundancy gain but also slight violations of the race model (only at the 0.15 decile). Given that their study involved 40 participants (versus the 76 participants presented here) it is possible that the effect was so minor that it was lost with the addition of participants. In other words, there may not have been enough power to ensure that there was no Type I error. As noted above, 68 of the 76 participants showed a violation of the race model at some decile, and, referring to Figure 2, the early deciles that Schroter, Ulrich, and Miller (2007) reported as at or near significance are also those that appear to be nearest the zero point (0.05-0.25).

The Visual-Auditory Redundancy Gain

The visual-auditory condition, the foundation of showing violations of the race-model inequality, was shown again to violate the race model. The results presented here were particularly compelling, expanding the deciles that were significantly violated.

Miller (1982) originally showed significant violations at the 15th through the 35th percentile (violations occurred 5th to 55th percentile), whereas in this study 0.15-0.65 deciles showed significant violations, confirming statistically the percentiles suspected to be violating the race model in Miller's original work. As stated by Miller (1982), this clearly shows that the race model cannot explain the redundancy gain effects. However there is still some question of why the same effect is not observed in either the auditory or visual condition alone. In other words, what is so different about the visual-auditory condition that leads to violations of the race model. Stated in the framework of the coactivation model, why do two sensory modalities co-activate faster to redundant stimuli, than in one sensory modality? The question is perhaps beyond the scope of what can be answered by these results, but it is not beyond speculation. It should be noted that Miller (1991) showed that if the stimuli were congruent, having high frequency tone paired with a visual stimuli high on the screen, resulted in violations of the race model as opposed to non-congruent pairings (low frequency tones paired with a visual stimulus high on the screen). In part it suggests that there is an effect of the stimuli binding into a coherent perception. Multi-modal studies outside of the redundancy gain literature have shown some results that lend credence to the idea that when multimodal stimuli are arranged into a cogent stimulus, the redundancy gain is enhanced (Laurienti, Krafy, Maldjian, Burdette, & Wallace, 2004; Mozolic, Hugenschmidt, Peiffer, and Laurienti, 2008). For example, Mozolic, Hugenschmidt, Peiffer, and Laurienti (2008) showed that when participants were presented with a red circle and heard the word “red” (congruent) there redundancy gain was greater, and violated the race model, than when the stimuli were incongruent, hearing “blue” and seeing a red circle. Interestingly, the violations of race model could be modulated by having the participant pay selective attention to either visual or auditory information only, suggesting potential distracter effects when an individual is trying to parse the sensory world versus integrating the senses. If this were the case, it might be possible to do a visual-only version of the redundancy gain paradigm that is perceived as one stimulus. For example, it may be possible to use a "pac-man" visual stimuli to create an illusory square. If the idea that integration of stimuli into one coherent perception is the source of redundancy gain with violations of the race model, then when the pac-men are arranged in an illusory square there should be greater redundancy gain than when they are not.

However, it may be possible the violations of the race model are simply an effect of combining two stimuli from different sensory modalities. To check for an expansion of this effect a vibrotactile version of redundancy gain testing is certainly reasonable, where the patient was tasked with responding to tactile stimulation to either the right or left, or both sides of the arm. This experiment could then be extended to the vibrotactile-auditory and vibrotactile-visual redundancy paradigms and perhaps could provide further evidence for or against multi-sensory enhancement of redundancy gain. As an important component, it could be used to identify possible future experiments by implicating a common area of coactivation across modalities. Conversely, if the same effect was not found, target those areas specifically associated with visual and auditory integration and motor response generation (e.g. the Superior Parietal Lobule, Molholm, Sehatpour, Mehta, Shpaner, Gomez-Ramirez, Ortigue, Dyke, Schwartz, and Foxe 2006). However, despite not being able to concretely answer what exactly causes the uniqueness of the visual-auditory condition when compared to single sensory conditions (as exemplified by Figure 8, 9 and 10 and Table 11), there are several other interesting points in the data.

Correlating the Redundancy Gain Measures

Through correlation analysis, it is also possible to suggest commonality in the underlying processes involved in processing the visual and auditory information. Interestingly, there were strong significant correlations between all of the redundant condition reaction times across the different sensory modalities, which suggest that at least some of the underlying mechanism is shared between the auditory, visual, and visual-auditory condition possibly including the integration point, decision point or motor generation. The race model violation index also correlated across the different senses. It was particularly well correlated between the visual and auditory conditions. Perhaps surprisingly, the next strongest correlation of 0.312 was between the visual and visual-auditory condition, while the weakest was the correlation of race model violation index scores of the auditory and visual-auditory condition, which was not significant at 0.213. Given that the auditory condition and the visual-auditory condition showed the highest numbers of violations of the race model and appear to be very tightly related, it is perhaps paradoxical that the correlation of the RMVI was the smallest, and not significant. However, this result may perhaps shed light on a potential explanation of how the enhancement of redundancy gain occurs in the visual-auditory condition. It may be proposed that the auditory condition, as the faster of the two, set a baseline response level, and those individuals who show some enhancement of the visual reaction time (those that show violations of the race model in the visual condition) provide a more robust coactivation effect, which in term means that the visual and visual-auditory differences are more strongly, and statistically, correlated. In other words, the speed of reaction times and violations in the visual condition may be a strong predicator of the overall visual-auditory violations of the race model since they are serving as a faster and/or stronger coactivation signal. There is no apparent way to place the visual auditory task into the hemispheric coactivation model (Miller, 2004), though perhaps a better way to test the model would be to play lateralized tones and display visual stimuli to each hemisphere in an attempt to make the experiment conform more to the model evaluation for the requirement of both hemispheres to be active.

Looking at the correlation between the mean redundancy reaction time and the RMVI, it is clear that, at least for the auditory only and visual only condition, there is a very strong correlation. This correlation suggests that the fastest individuals are also the ones that have the tendency to be at or violating the race model boundary. Looking at the visual-auditory RMVI, there is no mean redundancy measure that correlates strongly, though all three correlate with weak to medium magnitude. Clearly, the faster the mean reaction time, the higher the tendency to be at the violating end of the RMVI. However, again, the visual-auditory reaction task does not appear to be consistent with the results of the visual only and auditory only redundancy tasks.

Considering the correlation of the RMVIs with the visual working memory accuracy showed that the strongest, negative correlation was between the visual RMVI and the visual working memory accuracy ($r = -0.378$, $p<0.001$). The next strongest correlation was between the auditory RMVI and the visual working memory accuracy ($r = -0.276$, $p < 0.05$). Finally, the correlation between the visual auditory RMVI and the visual working memory accuracy was weak and non-significant ($p = -0.093$, $p = 0.463$).

These results could be interpreted as in line with the work focusing on the notion of perceptual speed correlation with measures of intelligence and/or general intelligence (e.g Mackintosh and Bennett, 2001). If an individual can process visual information faster or more efficiently, it would not be surprising for those individuals to perform high on the visual working memory task and also on the lower end of the RMVI index for the visual redundancy gain task. It is interesting to note that there is a correlation between the visual RMVI and the visual-auditory RMVI, and that there is a large correlation between the visual RMVI and the visual working memory accuracy, but that there is not a correlation between the visual-auditory RMVI and the visual working memory accuracy, presenting a potential paradox worth further exploration.

Overall, this study has provided the most comprehensive look at the different basic sensory redundancy gain tasks currently found in the redundancy gain literature using a single set of participants. Across all levels of analysis, it appears that the visual-auditory redundancy task was fairly unique when compared to the visual only and auditory only paradigms. Additionally, it is not clear exactly how the visual-auditory task and results work within the hemispheric coactivation model proposed by Miller (2004). Another important conclusion is that the RMVI correlations showed that there was a fairly robust relationship between the auditory and visual redundancy condition ($r = 0.538$, $p < 0.01$), but that the relationship between the visual only or auditory only redundancy and the visual-auditory redundancy condition were not nearly as strongly correlated ($r = 0.312$, $p < 0.01$ and $r = 0.211$, $p = 0.067$). The correlation between the visual only and auditory only RMVI suggest that a similar mechanism underlies violating the race model between these two conditions (the hemispheric coactivation model).

However, the lack of such a robust relationship for the visual-auditory task might point to a different mechanism of action involving bind of the stimuli into a cogent perception. Finally, it appears that there may be some interesting relationships between processing speed, redundancy gain, and memory performance tasks which up to this point has not been discussed in the literature. Clearly, there are a large number of questions concerning the basic psychophysics of the redundancy gain phenomenon.

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